Repeatability and High Speed Validation of Supplemental Lead-Extrusion Energy Dissipation Devices

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Abstract:

Recent research on supplemental damping enabling low to no damage structures has led to new devices, such as lead-extrusion based high force-to-volume (HF2V) devices. They provide significant energy dissipation and force capacity in a small volume, enabling a range of novel low to no damage connections and systems. However, despite several research study tests and a limited range of velocity testing, they have never been tested across a realistic velocity range or for robustness to manufacture and design across several devices. These issues are hurdles that limit professional design uptake and add uncertainty and risk to their use in design. To address them, a serious damage-free dissipation device characterise its force capacity and variability due to manufacture (repeatable quasi-static force) and velocity input (peak force to connections). These outcomes are critical to size all the connections and foundations for the resultant demands, and ensure robust, effective design.

This manuscript presents the quasi-static testing of 96 devices designed for the same quasi-static force capacity, as well as high-speed prototype testing at velocities up to 200mm/sec. Quasi-static tests show device forces vary with standard deviation, $\sigma < 6.2\%$ of design and average force. Peak input velocities of ~200mm/s produced peak resistive forces of ~350kN and increasingly weak velocity dependence as device input velocity increased, which is an advantage as it limits large demand forces to connecting elements and surrounding structure if larger than expected response velocities occur. Overall, the devices show stable hysteretic performance, with slight force reduction during high-speed testing due to heat build-up and softening of the lead working material. This testing quantified important HF2V device dynamics and robustness for designers and is an important step towards design uptake.

Keywords: Earthquake, Seismic Response, Energy Dissipation, Lead Extrusion, HF2V, High-speed, Robustness.

Data Availability Statement: The device test data used to support the findings of this study are available from the corresponding authors upon request

1.0 Introduction:

In recent damage avoidance design and supplemental dissipation device research, high force-to-volume (HF2V) lead-based dampers have been developed that provide large resistive forces while maintaining compact outer dimensions able to fit within typical structural member dimensions [1, 2]. These devices have been implemented into several large-scale experiments, using both jointed-precast concrete and steel beam-to-column rigid connections [3, 4]. These quasi-static experiments involved limited numbers of custom manufactured devices. While the custom made devices delivered repeatable hysteresis curves, it is unknown whether outsourced manufacturing of large numbers for a real structure would yield the same consistency. Equally, it has not been possible to test the HF2V damping devices in near full scale structures at representative peak earthquake velocities, so that there is uncertainty around the peak forces that would be obtained in these weakly velocity dependent devices [1]. These two uncertainties in robustness to manufacture and velocity dependence are significant limitations to design and uptake.

In a bulged-shaft lead extrusion damper, such as the HF2V device, lead is confined within a cylinder with the bulged-shaft through the centre, as shown in Figure 1. As the shaft is forced through the cylinder, the lead is forced to flow through the annular restriction created by the bulge, where this plastic flow absorbs a large amount of energy and provides high resistive forces for a relatively small device. Because the device is weakly velocity dependent and forces may change over repeated large cycles [1], careful characterisation of the velocity dependence is required.

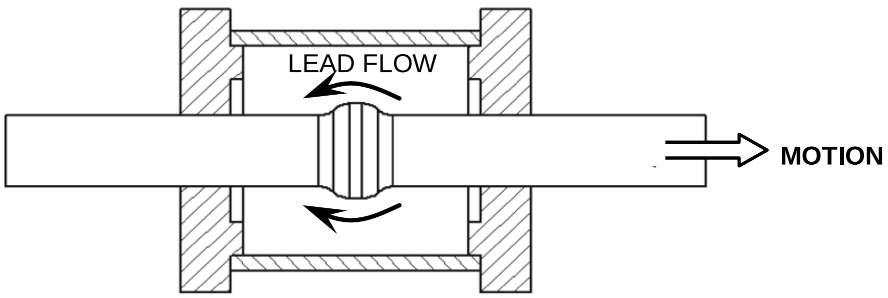


Figure 1: HF2V device schematic.

In particular, high speed testing at speeds that represent maximum response velocities that might occur in large near-fault events with very high local accelerations are necessary to facilitate uptake of HF2V devices into new and retrofit structures. Although the HF2V dampers are only weakly velocity dependent in prior studies, any device that exhibits velocity dependence should be thoroughly tested before being used in a structure, which could include MR dampers, ER dampers, and a range of other emerging devices [5-12].

In particular, it is critical to know the realistic peak forces that might be encountered to ensure connections between device and structure are designed to avoid failure under these loads. In addition, it is increasingly important to better understand the peak structural base shear forces that might occur as a result of large, velocity dependent added resistive loads. These peak forces have not been significantly investigated from a design of device-enabled structures perspective, although limited case examples exist [6, 13, 14].

Equally significantly, unplanned variability between device forces, seen in different peak forces in devices under quasi-static testing, could result in significantly different resistive loads across a structure utilising several such devices. These differences could induce higher mode or/and torsional responses not necessarily planned in the initial seismic design. Such variability could, in turn, create greater irregularity in the structure and its response than was planned in the design, leading to greater than planned loads and potential increased risk of damage [15].

Hence, professional design uptake of HF2V devices, which would be used in relatively large numbers of 50-200 in real buildings, requires a greater knowledge of the repeatability of device force in regular manufacture and of the peak forces and force velocity relationship expected at realistic peak response velocities. The recent use of 96 HF2V devices in a new hospital in Christchurch, New Zealand following the 2010-2011 earthquake sequence [16], provided the opportunity to evaluate and quantify these behaviours. The results should also better inform designers to the potential and limitations of these devices so they can be better integrated into the design and analysis process.

2.0 Methods:

2.1 Devices:

A total of 96 HF2V devices were developed for the Kilmore Street Medical Center (now named Forte' Health). The building is an approximately 45m x 40m, predominantly steel structure. The suspended steel-concrete composite floors slabs are supported by eight sets of coupled steel post-tensioned braced frames around the perimeter to provide lateral load resistance. This PRESSS (Precast or Prefabricated Structural Seismic Systems) design approach uses an "Advanced-Flag Shape" system, where displacement proportional and velocity-proportional energy dissipation mechanisms are combined in parallel to the recentering contribution from the un-bonded post-tensioned bars. The overall outcome results in a dissipative and self-centring rocking structure, with details in [16]. The HF2V devices provide passive dissipation and there are 12 per rocking frame, with plan and locations shown schematically in Figure 2.

Two types of HF2V device were designed based on the stroke required for the specific structure location. There were 32 short stroke devices with peak-peak stroke of 120mm allowed by design, and 64 longer stroke devices with 140mm stroke allowed by design. All devices were designed for peak forces of approximately 350kN, equating to quasi-static peak forces of approximately 260kN based on the work in [1]. Thus, while stroke length in testing varies with device based on its use in the final structure, the expected forces are designed to be the same.

All devices were manufactured in bulk by external contractors. The device design ensured, for example, that while cylinder lengths changed depending on stroke, the end-caps were the same and the shaft diameters and shaft bulges were also the same to provide the same quasi-static force capacity by design. Note that shaft diameters of 30mm of high strength AISI 4340 steel ensure no shaft yielding occurs before a minimum of 600kN, which is well above expected service loads. All devices were pre-stressed using the end-caps to a load of 200 kN to ensure consistency.

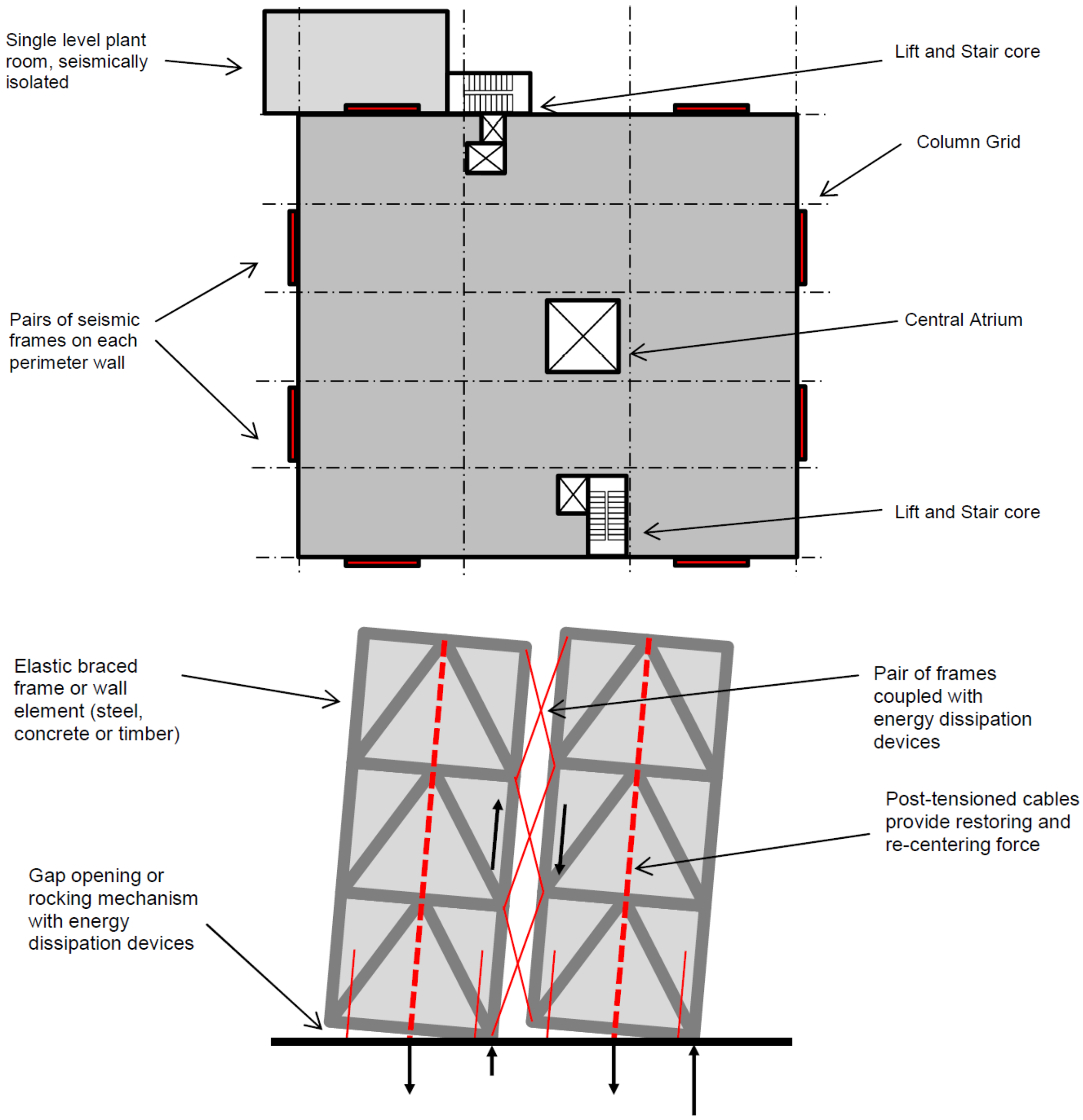


Figure 2: (Top) Plan view of Kilmore Street Medical Center showing 8 pairs of rocking frames. (Bottom) each pair of frames has 12 HF2V devices mounted in pairs, with 8 at 4 points at the bottom of the frames and 4 at the 2nd and 3rd levels, where the diagonal lines at each level indicate added buckling restrained braces [16].

2.2: Quasi-Static Tests:

All 96 of the lead extrusion dampers supplied underwent non-destructive quasi-static batch-testing at velocities of approximately 1.5mm/s using an Avery 1000kN static testing machine where velocity is manually controlled and may thus vary slightly. This speed is the effective peak velocity this machine produces for these force levels. Displacement was measured independently and the force was acquired using a load cell. Each HF2V device was quasi-statically tested for two uni-direction test cycles comprising ±60mm for the short stroke devices and ±70mm for the longer stroke devices. The HF2V device was inverted after each input motion to reverse direction. Force and displacement were recorded for each cycle and plotted separately for each device, where these loops are stitched together as one test begins at the end point of the prior test, with opposite sign of force, due to the inversion of the damper. Devices that deviated more than 20% from the expected force levels had more pre-stress applied to the lead to remove voids or bubbles, thus increasing capacity [1]. However, only the first test run results are shown in this study so variability due to manufacture can be assessed.

2.3 High Speed Tests:

To undertake high speed testing of HF2V devices, a maximum likely response velocity for this structure was necessary. The most likely applications for HF2V devices are within rocking connections or rocking walls, or within structural bracing. While the maximum velocity imparted into a damping device is dependent on a number of factors, such as the eccentricity from a rocking edge, structural natural period, and the maximum ground motion velocity, most applications would dictate a peak velocity for a Maximum Considered Event (MCE) on the order of 100-300 mm/s, which in this case was specified by the designer based on nonlinear simulation yielding response velocities across the devices as located. It is noted that for different structures, such as steel moment frame connections in [4] and device locations, these velocities could be much higher. This peak velocity is well beyond the maximum input velocity previously tested in structural scale studies [3, 4]. Hence, the test machines must be able to provide up to 400kN of force at up to 200mm/sec speed.

Many test machines in New Zealand are either low force (up to 100kN) and high velocity (400 mm/s or higher) or high force (10 MN or higher) with very limited velocity (up to 10-15 mm/s). Very few local systems can provide capacity in the required intermediate range of force and velocity. In addition, many machines can only provide a high velocity for only one-to-two cycles due to limited accumulator capacity. Therefore, two considerations were made: **1**) The peak, one-shot velocity that could be obtained, which is typically limited by the system’s accumulators; and **2**) the maximum sustained repeated cyclic velocity, which is limited by the rate the pump can supply high-pressure fluid.

Given the 400kN requirement, no hydraulic test system could be located that allowed the devices to be tested in a direct-drive sense. The closest, at Quest Integrity (Gracefield, Lower Hutt, New Zealand), was an Instron 1344, shown in Figure 3a, capable of 250kN peak force and cross-head velocities up to 400 mm/s at near full load, which is close to the requirements. A 2:1 lever-set-up, shown in Figure 3b, was designed to reduce the velocity and increase the force capacity, allowing up to 500kN and 200mm/s to be imparted into the HF2V damping device, thus meeting the required test characteristics.

Data acquisition was provided by a rotational encoder and string-line and force was provided both directly from the cross-head and through a 500 kN Universal load cell. Force and displacement was recorded directly off the device due to the slight variation in lever-arm length through the range of motion. This variation is due to elastic flexibility of the lever-arm system and friction within the pin joints reducing force transferred from the machine. The load cell force is thus the true input force.

a) Instron 1344 at Quest Integrity Ltd, Gracefield.

b) Lever-system to increase force capacity

Figure 3: Details of the device test configuration.

HF2V devices were subjected to fully reversed cycles at near full-stroke (±45mm amplitude) at device velocities from 2.5 mm/s through to 200 mm/s, corresponding to 5-400mm/s at the Instron cross-head. For velocities up to 25 mm/s, 3 or more fully reversed cycles could be sustained without loss of hydraulic pressure and consequently loss of machine position control. At higher velocities (50, 100 and 200 mm/s into the device), only part of the input profile could be sustained before the loss of position control. Multiple devices of the same design were tested to indicate repeatability between devices.

Finally, to test the influence of heat build-up and softening of the lead, 10 fully reversed cycles at near-full ±60mm stroke were undertaken at the maximum sustainable velocity of 10 mm/s. Beyond this velocity, only a maximum of 3 cycles could be achieved before a loss of hydraulic pressure. Hence, this specific test is designed to quantify worst case device force degradation over several, large cycles.

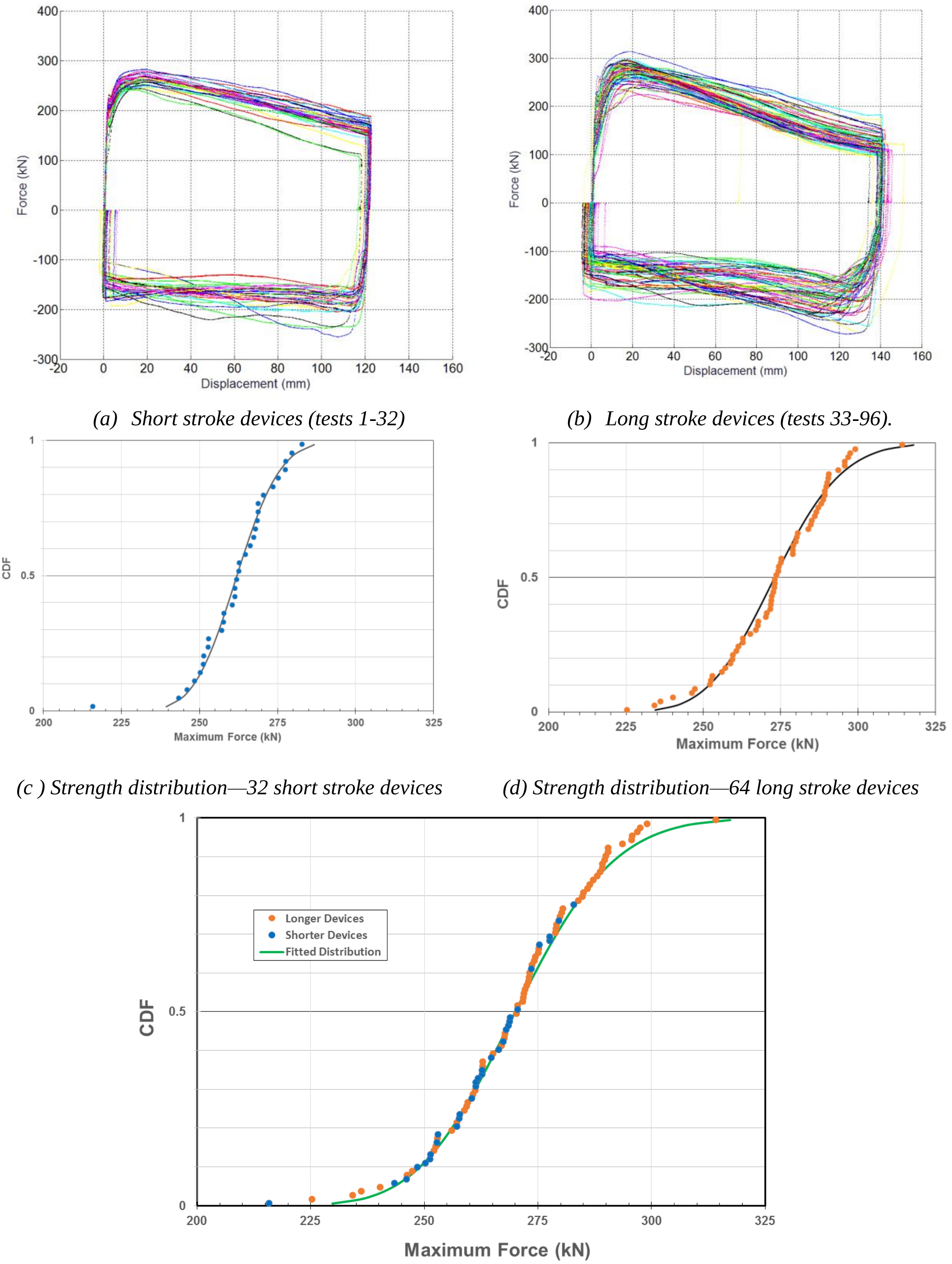
3.0 Results and Discussion:

3.1 Quasi-Static Tests:

Figure 4 presents the quasi-static tests results from the shorter stroke devices (N = 32, tests 1-32) and the longer stroke devices (N = 64, tests 33-96). There is some variability between devices of each type, as seen in the graphs, but force levels are consistent with those seen in prior prototype devices. In particular, short stroke devices have mean (±standard deviation) peak force of 261.5 (±12.9) kN, and long stroke devices provide 273.2 (±17.3) kN. These standard deviations relate to ±4.9% and ±6.2% of average peak force, and directly quantify the variability due to manufacture in bulk.

The CDFs in Figure 4 and associated statistics also show the measure of required over-strength due to manufacturing variability. In particular, 95th percentile ($+2\sigma$) device forces are 278kN for the shorter devices and 293kN for the longer devices. Given a design force of 250kN, compared to an average of 269.2kN over all devices, the over strength bias for the 95th percentile is 6.9% for short devices 12.7% for long devices. Equally, the percentage below a minimum specification of 260kN minus 1σ or 6.2% of 260kN (244kN) is 1 device or 3% for the short devices and 4 devices or 6% for the long devices. These few devices could be easily pre-stressed again, as was done at minimal cost for outliers, to ensure they met specification. Overall, the distributions are relatively tight to specification and the average values obtained. Very few would require reworking. Finally, any similar specification system to ensure a tighter distribution of manufactured peak device forces, including reworking, could be employed.

Figure 4e presents the overall distribution of strength measured in all 96 tests, regardless of stroke length. It should be noted that the design strength of all devices was set at 250 kN. Based on the measured capacities there is, on average, a strength bias of ~8% above the design strength with the 95^{th} percentile of ~300kN being 20% above design strength. However, more importantly, for capacity design purposes it is necessary to design fixtures and other structural members by increasing the strength by an overstrength factor from the weakest link in the resistance chain. In this case, the HF2V devices are intended to be the “weak” or sacrificial link allowed to give way. Results in from the distribution in Figure 4e suggest an overstrength factor of ϕ_0 = 1.2 above the design (specified) device strength would be in order in accordance with customary capacity design principles. This factor and approach gives the designer confidence the devices will not lead to yielding or damage in other parts of the structural system.



(a) Short stroke devices (tests 1-32)

(b) Long stroke devices (tests 33-96).

(c) Strength distribution—32 short stroke devices

(d) Strength distribution—64 long stroke devices

(e) Strength distribution for all 96 devices. Median strength = 270 kN, Dispersion of strength (COV) = 7.2%

Figure 4: Quasi-static results for the 96 HF2V devices showing statistical distribution of strength.

Recall that the devices were tested uni-directionally and thus each loop is stitched together from 2 quasi-static tests. The small directional variability seen in the results, where the negative direction is smaller than peak force in the positive direction, is due to initial pre-stress applied by the test in the positive direction that must be first overcome when returning the device a full stroke in the opposing direction. Hence, this directionality is expected, and could be readily ameliorated by pre-stressing the devices using both end caps.

Finally, each test shows the initial peak force as device motion begins and the device changes from a static resisting force to a kinetic resistive force as the lead begins to flow and the shaft moves. As a result, the peak force is early in the cycle, and forces drop slightly. This behavior is typical of these devices when tested over longer strokes than those presented in the initial works, which had far shorter strokes considering their location inside beam column connections [1, 4, 17, 18].

The use of independent device testing could be assumed to imply that it may not perform this way in service, or that the required reversing of the devices in quasi-static testing could increase the variability of the results. However, prior works have shown that both assumptions are not accurate (e.g. [4, 18, 19]). In particular, they show a solid material device has no gravity dependence and this simple test captures device behavior consistently and well. Equally, these references show that when used in large scale systems, the device behaviour almost exactly matches results seen in separate testing like that done here. Thus, there is little reason to assume different performance in situ or as a result of the quasi-static test method.

The overall results show remarkable consistency for a low-cost and simply manufactured device. Each device costs approximately NZ$1000 (US$700) and were machined using several local machinists. The assembly, including lead pour and pre-stress, was done at a central location. Thus, the device consistency of ±6.2% or less from the average (design) device force indicates these devices are very robust to manufacture and assembly, largely due to their relatively simple manufacturing process.

3.2 High Speed Tests:

Figures 5-8 present device results for different input velocities. Force, displacement and velocity values represent those within the devices and not those of the machine cross-head. Figures 5-6 show input displacement is very similar between tests and the machine cross-head tracks the command input well. However, in Figures 7-8, it is evident that once the hydraulic pressure in the accumulators is lost, displacement tracking is very poor and inconsistent, as expected. This difference is simply due to the limitations in the hydraulics used to drive the test machine.

Overall, Figures 5-8 clearly shows the HF2V devices exhibit only very weak velocity dependence, as expected [1]. This observation is attributed to the fact that the overall resistive force is made up of a combination of frictional resistance and extrusion resistance. Frictional resistance is generally considered to be velocity-independent, and extrusion only weakly dependent on velocity.

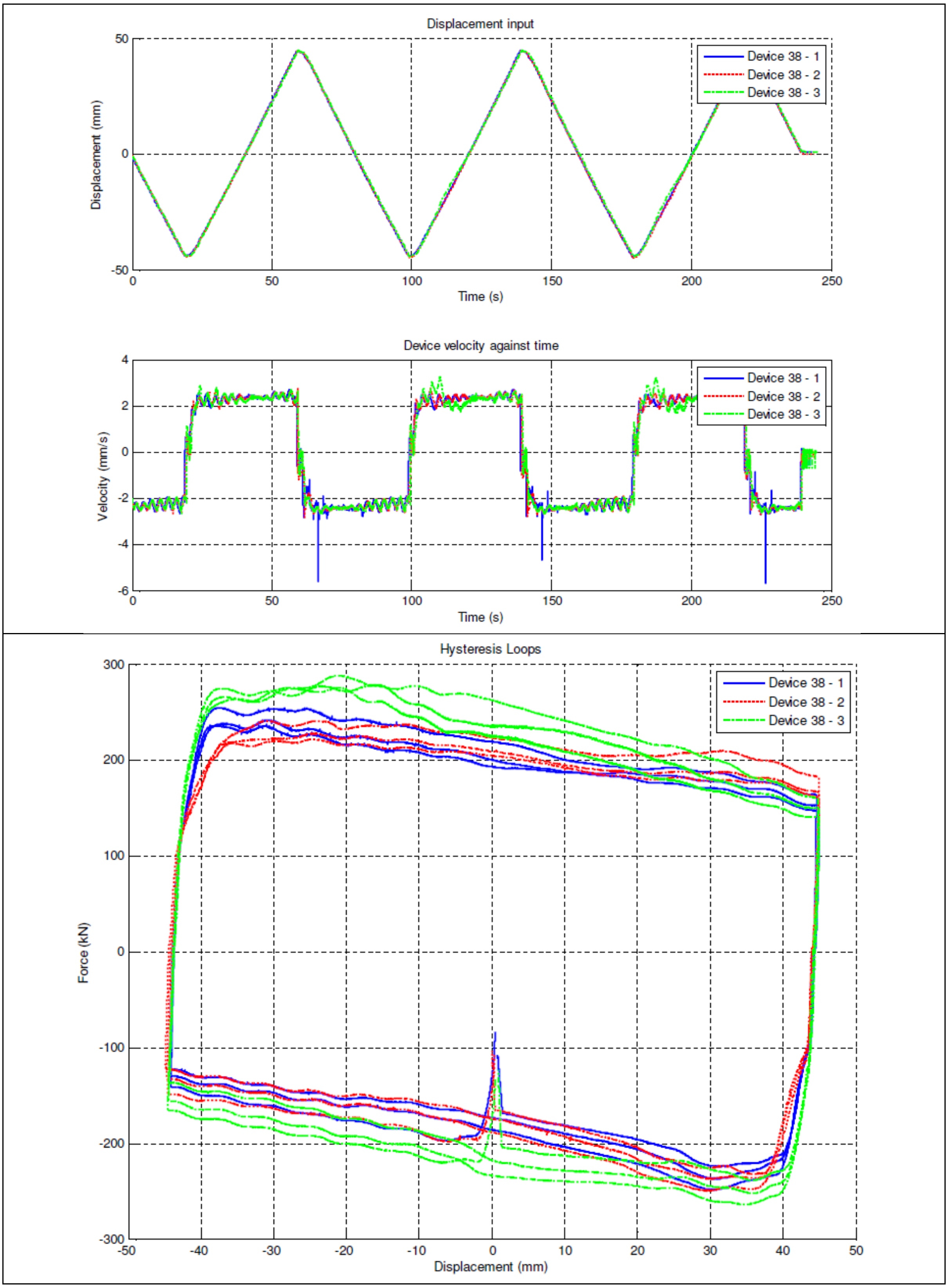


Figure 5: Representative results showing 3 fully reversed cycles at 2.5 mm/s device velocity command with inputs of displacement and velocity (<u>top</u>) and resulting hysteresis loops (<u>bottom</u>).

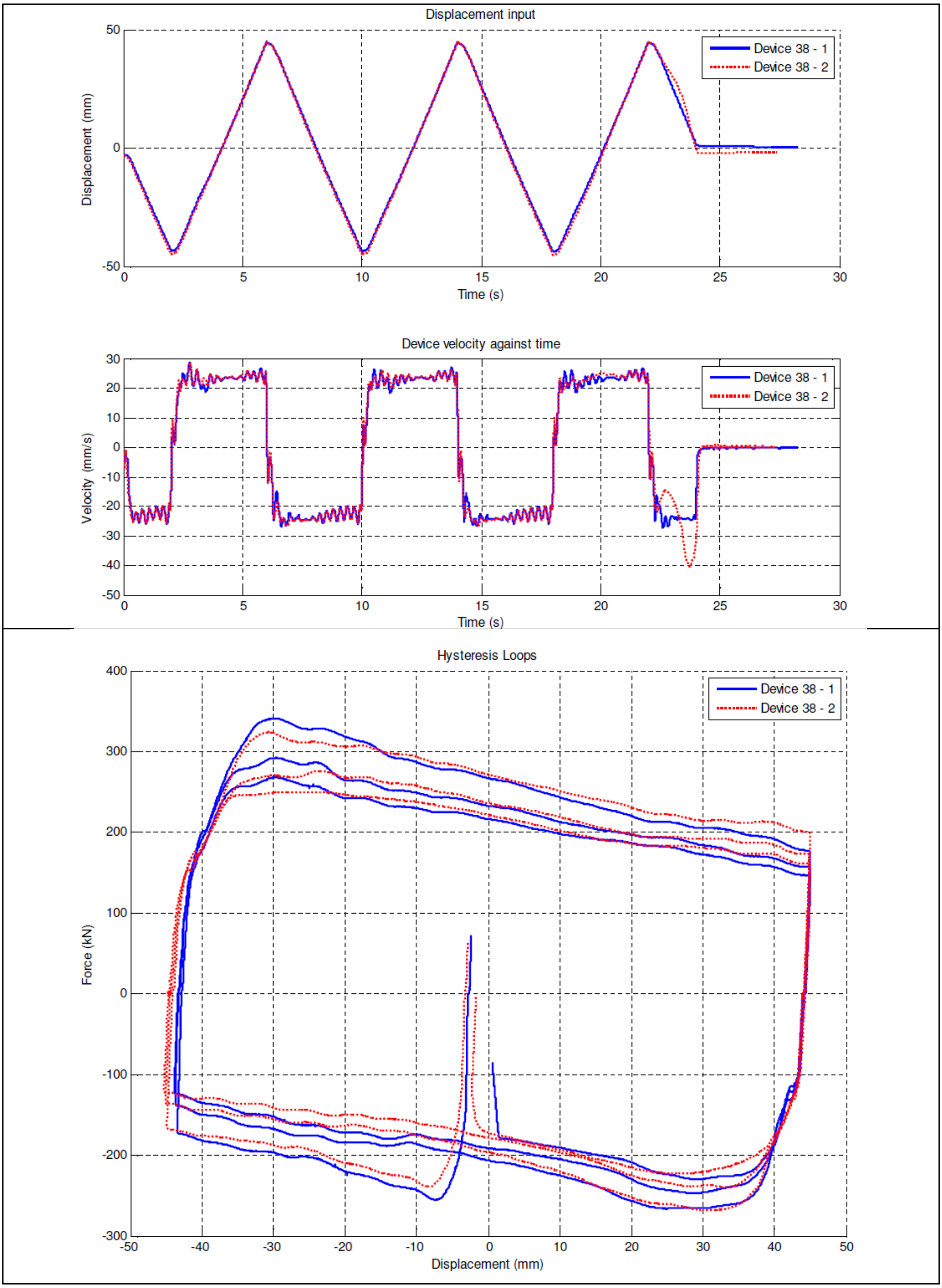


Figure 6: Representative results showing 3 fully reversed cycles at 25.0 mm/s device velocity command with inputs of displacement and velocity (<u>top</u>) and resulting hysteresis loops (<u>bottom</u>).

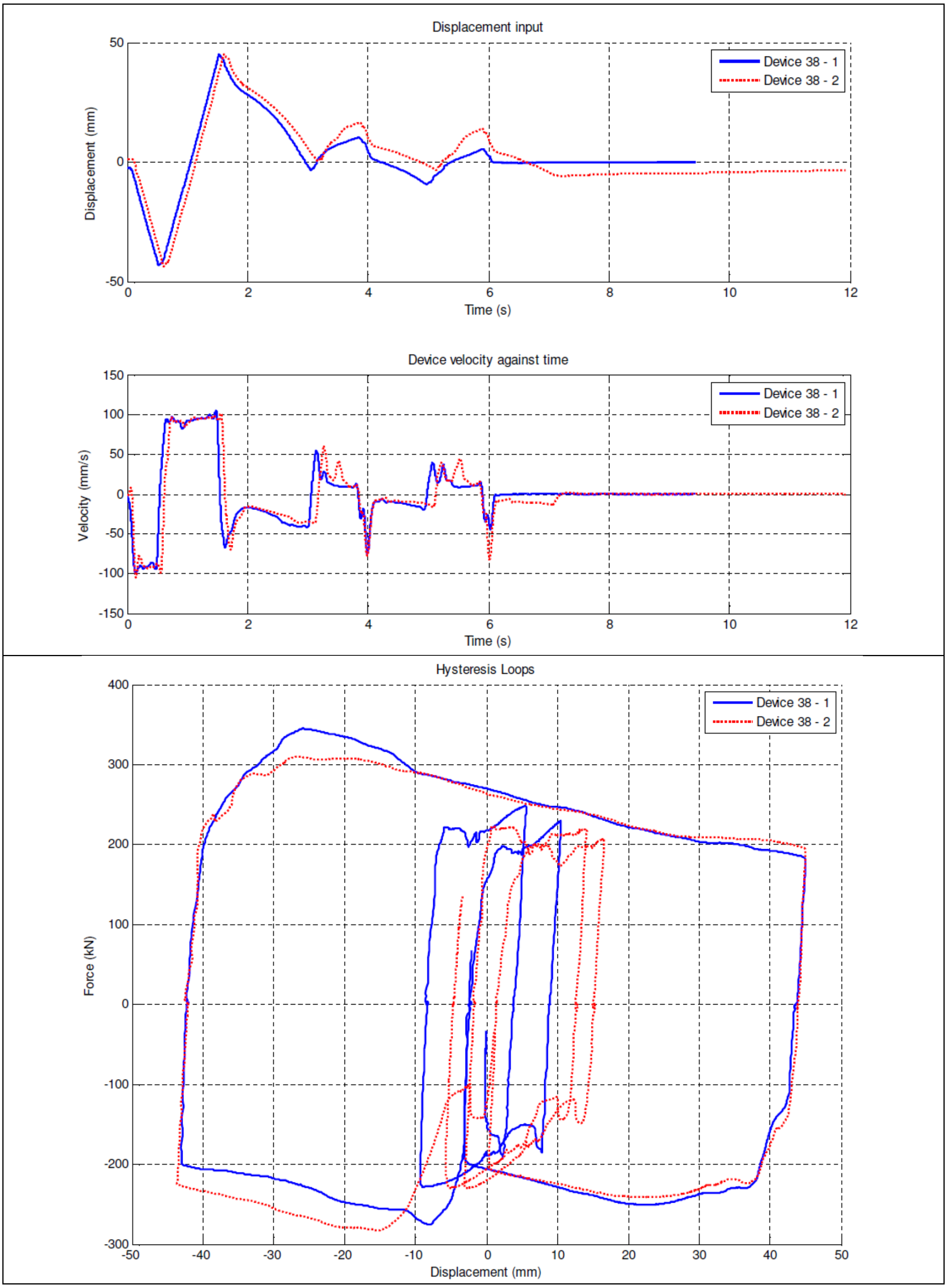


Figure 7: Representative results showing 3 fully reversed cycles at 100.0 mm/s device velocity command (but not achieved) with inputs of displacement and velocity (<u>top</u>) and resulting hysteresis loops (<u>bottom</u>).

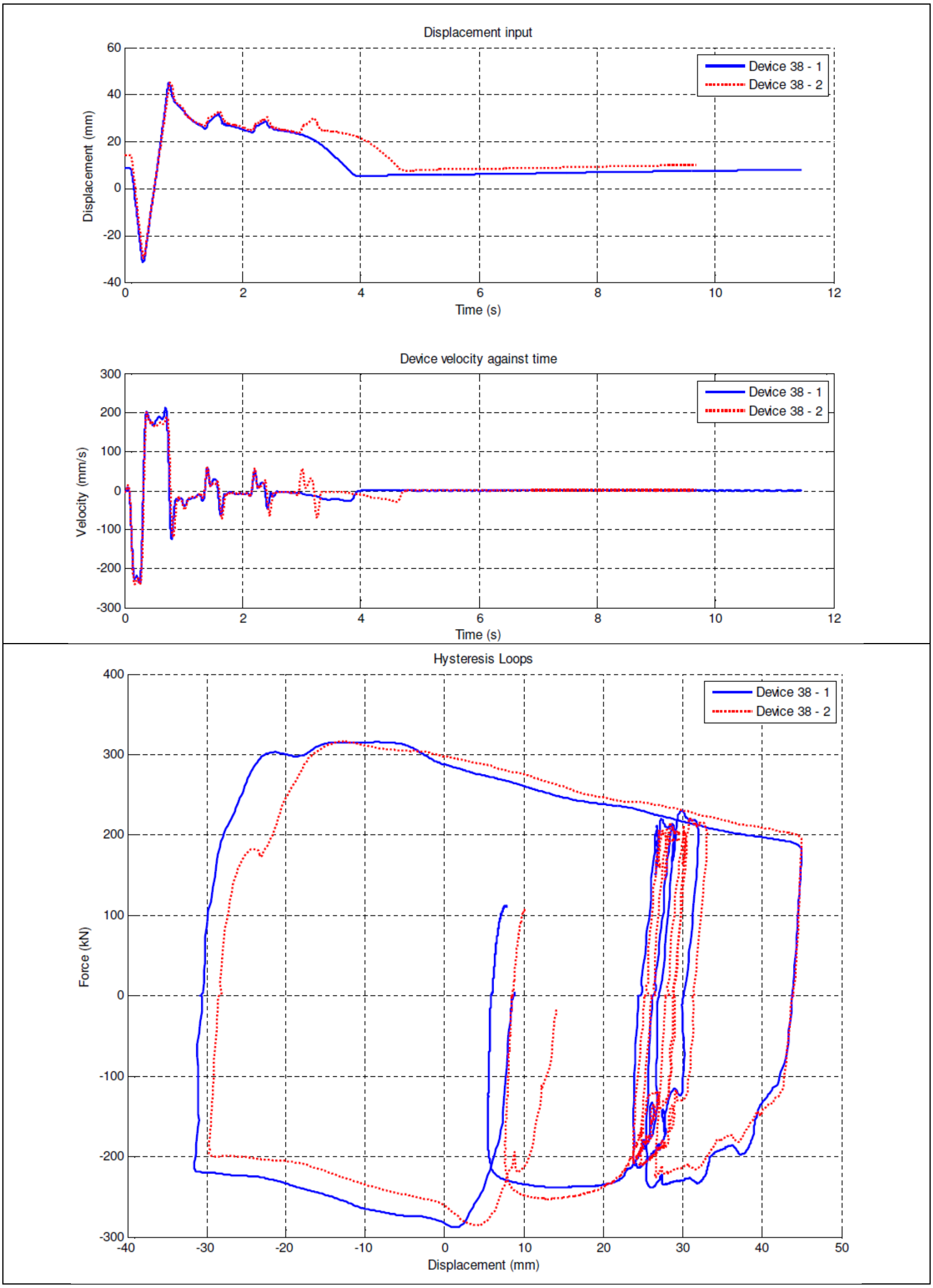


Figure 8: Representative results showing 3 fully reversed cycles at 200.0 mm/s device velocity command (but not achieved) with inputs of displacement and velocity (<u>top</u>) and resulting hysteresis loops (<u>bottom</u>).

In addition, it is apparent in Figures 5-8 the friction component may reduce with higher input velocities, as the transition from static to kinetic friction is more rapid. This behavior is seen where the force response reaches a peak at initial motion inputs and then decreases for the significant majority of the motion where velocity is a maximum. Therefore, this reduction at higher velocity balances out the increased extrusion force, to provide a device whose resistive force is increasingly independent of the input velocity as velocity rises. This outcome can be considered advantageous from a structural design perspective, as high response velocities will not impart concomitantly increasingly larger damping forces into the structure, and thus will not require stronger reaction bracing at the device connections nor deliver larger base shear loads to the foundation.

Hence, compared to a viscous damper that can be much more strongly velocity dependent [20-25], these devices have an increasingly smaller increase in force as velocity rises, all else equal. As a result, unlike a linear viscous damper and other similar devices, the peak forces that would be expected from peak structural velocities are effectively limited. The exception would be those viscous dampers with non-Newtonian fluids with significantly nonlinear behaviour that also limits peak forces as velocity increases [21, 24-26]. This limiting implies easier design of connections, device components like the shaft, and of the overall structure considering total reaction forces and base shear, as the demands on all these elements is thus limited.

Figure 9 presents results from 2 identical devices subjected to 10 fully reversed cycles at the maximum sustainable input velocity of 10 mm/s device velocity. There is an evident reduction in resistive force due to the heating effects and softening of the lead as the cycles proceed. The devices, post-test, were quite hot to the touch, although temperature was not measured. Overall, peak forces drop from approximately 300kN on the first cycle, down to about 180kN (~40%) over the 10 cycles, which is a potentially a significant reduction.

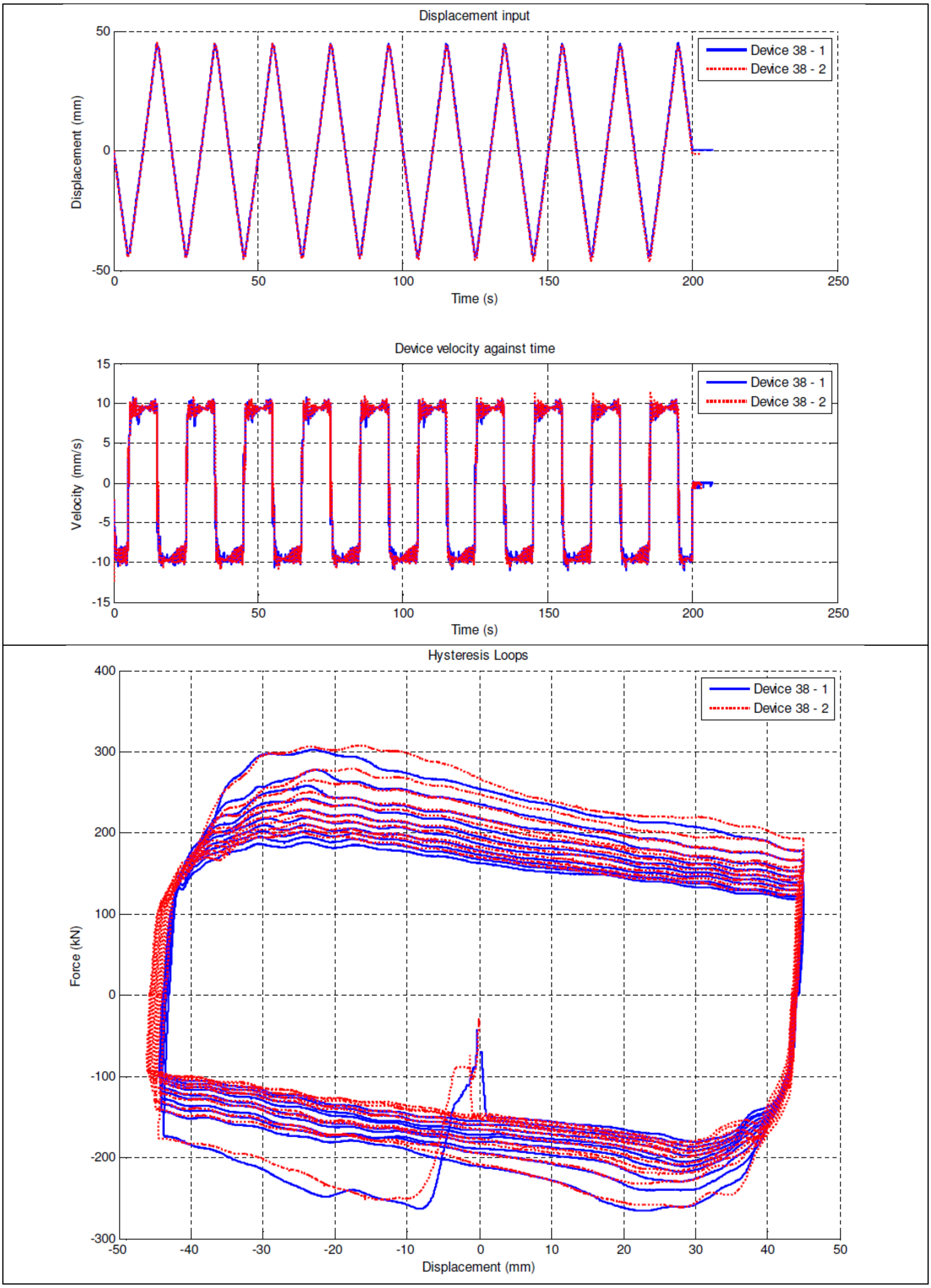


Figure 9: Two identical devices subjected to 10 fully-reversed, near full-stroke displacement cycles at 10.0 mm/s.

While the results imply a maximum loss of up to 40% in resistive force, it is important to note that it is a temporary effect. Once the HF2V devices were allowed to cool after testing, resistive forces returned to their original values within several minutes. Thus, full resistive forces would be available for a subsequent event, even if it occurred 40-45 minutes later as was the case on February 23, 2011, and subsequent large events, in Christchurch, but is more rarely the case elsewhere.

Moreover, the input of 10 fully reversed, near full-stroke cycles is unlikely to ever be experienced in service. The stroke tested here, represents a typical peak response amplitude for the Maximum Consider Seismic Event (MCSE) used in structural design. However, in such a response, only 1-2 cycles, rather than 10 fully reversed cycles, could be expected at this peak amplitude. Hence, the reduction after 2 cycles of approximately 10% is the more likely outcome in such large events, and implies a relatively small reduction in use that is regained shortly after an event.

Finally, both devices in Figure 9 respond in a near identical fashion. This result, coupled with those in Figure 4, further validates the consistency of the device forces obtained, where, in this case, the 2 devices were selected at random from the 64 longer stroked devices. Importantly, even the degradation, cycle to cycle, as the lead heated, was consistent.

It is also important to put the results of Figure 9 into context. Yielding steel fuse-bars and buckling-restrained braces would likely have failed due to low-cycle fatigue if they were subjected to 10 cycles at this level of yield displacement [27, 28]. In addition, their stiffness and strength degradation would be permanent and not recovered post-event, requiring repair or replacement while leaving the structure more vulnerable. Likewise, if energy was absorbed via sacrificial damage, it is unlikely that the building would be serviceable or have much remaining capacity if it were to be subjected to this level of demand in the nearer term, as would have been the case in Christchurch, 2011.

Overall, these high speed tests have provided a first insight into the velocity dependence of these devices at realistic input velocities. As noted, these could be much higher, approaching 1m/sec, depending on the application and where the devices are designed into the structure. However, these tests are at far higher velocity than others we have found in the literature or elsewhere for HF2V or similar dissipation devices, although significant degradation was seen over many cycles in earlier, similar devices designed for base isolation [29]. It is also expected, as noted previously, that viscous dampers would not suffer this same effect, but would have a stronger velocity dependence in some cases, barring non-Newtonian fluid viscous dampers, yielding potentially undesirable higher reaction forces in some cases [20-25].

A limitation of these tests is the inability to exceed ~20mm/sec for any extended period of cycles and peak velocities for only a single cycle. Availability of systems within New Zealand that can provide such capacity are being developed, but were not available at the time of this work, and represent a significant capital investment given the required pumps and accumulators necessary to supply actuators with enough consistent flow to achieve high forces and velocities the actuators are capable of providing. As such systems become available, it would be useful to revisit this work and, in fact, many emerging devices to assess their velocity dependence and degradation at realistic velocities and force levels.

4.0 Conclusions:

HF2V devices are an emerging, damage free device for dissipating large amounts of seismic response energy. However, their velocity dependence, and the consistency and robustness of base resistive force capacity in larger-scale manufacture have not been quantified. These issues provide an impediment to uptake in new or retrofit design and have been quantified in this study.

Quasi-static testing of 96 devices for a newly designed hospital in Christchurch indicated that base force capacity of mass produced devices deviated ±10% from the design quantity, with most well within this value. High-speed testing at device input velocities of 2.5 to 200 mm/s quantified a weak velocity dependence that reduces as the velocity increases to a point of being almost velocity independent due to a combination of a loss of frictional resistance at high speed and an increase in extrusion resistance. These two effects largely counteract one another, to produce resistive forces not affected by the shaft velocity. As a result, the total peak force and thus the peak demands on structural connections and foundations are effectively limited or capped using these devices.

Sustained cyclic testing showed that these devices do suffer some dynamic force degradation due to heat build-up softening the lead working material. However, these effects are temporary and the strength capacity is restored once the devices cool down after testing. As the lead working material is the only part of the device undergoing plastic deformation and all other parts remain within the elastic region, low-cycle fatigue is not an important design consideration.

Overall, these HF2V damping devices are shown to produce consistent resistive forces in mass manufacture that are almost independent to input velocity at maximum likely structural input velocities, and the devices show a strong robustness to repeated cycles as well as to manufacture.

5.0 Acknowledgements:

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